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Bird population changes reconstructed from isotopic signals of peat developed in a nutrient enriched tundra

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HIGHLIGHTS

- Five peat profiles deposited near seabird colony in Spitsbergen were studied.
- Peat profiles were dated with radiometric methods.
- Bird colonization was recorded in C and N stable isotopes.
- Peats located in the western part of the fjord are older than in the eastern part.
- Climate changes after the LIA initiated expansion of birds into the fjord.

GRAPHICAL ABSTRACT

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ABSTRACT

Five peat sequences were studied to identify the time the little auk *Alle alle* colonies originated in the Hornsund area (Spitsbergen). Elemental and stable isotope analysis of nitrogen and carbon was applied as markers for bird activity. The peat sequences were dated with ^{210}Pb and radiocarbon methods. The results showed that peat development related to seabird activity is significantly older (at least 300 years old) in localities closer to the fjord's mouth (west) than those located deeper in the fjord (east), which are ~100 years old. Isotopic signals indicated that bird activity in the western localities decreased simultaneously with the growth of the eastern colonies. Colonization by birds of new localities correlated with the termination of the Little Ice Age and the meaningful decrease in the glacier area of the region. Hence, we suggest that the availability of new localities for nesting in talus cones, nival moraines and lateral moraines on gentle mountain slopes with south-eastern exposition attracted the little auk due to better thermal conditions, isolation from strong westerly winds and better protection from predation by gull *Larus hyperboreus*. The expansion of little auks to the new localities was fast (20–30 yrs), and there are no records of changes in bird impacts on the tundra environment after 1920.

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1. Introduction

Climate conditions in the High Arctic effectively limit the productivity of terrestrial ecosystems (Natali et al., 2012; Lara et al., 2018). As a consequence, soil cover is usually thin and does not support the development of most vascular plants. Thus, peatlands are the most widespread type of vegetation in the Arctic. These ecosystems are sensitive to climate change because their development depends on relationships between temperature, precipitation, snow cover, etc. In addition to the harsh climate conditions, the low availability of nutrients is also a limiting factor in peatland development in the Arctic. The most important exceptions are the flats located under bird colonies, which are fertilized with nutrients from bird guano that is washed out from

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the colony area by precipitation (van der Knaap and van Leeuwen, 2004). The origin and existence of these peatlands are strongly related to the time of origin of the bird colonies, nest density and bird activity. The latter parameter is partly related to species composition in a bird colony and can be characterized by bird numbers, attendance patterns, breeding-season duration, number of chicks raised etc.

Several conditions must be fulfilled for birds to settle at a high density within a limited area. The most important conditions are food resources at sea and availability of space for nesting that is protected from predators. Marine ecosystems are the most important food resource for Arctic birds. Usually, seabirds feed at sea and breed and raise chicks on land in large colonies. This characteristic transfers large amounts of matter from the ocean to the land (Mulder et al., 2011; González-Bergonzoni et al., 2017). Defence from predators is addressed by nesting in cliff ledges, crevices or in burrows, and by nesting at high densities. The last factor was studied in detail, and the results showed that more central locations in the colony are often occupied by older or higher quality individuals (Krause and Ruxton, 2002).

Food webs in the Arctic are based mostly on marine producers including diatoms, flagellates and ice algae. In these food webs, copepods and krill are the main herbivores. The higher trophic levels are represented by zooplanktivorous predators, e.g. fishes, and the highest trophic level is occupied by marine mammals and seabirds. As most seabirds nesting in the Arctic feed mainly or exclusively on marine invertebrates and fishes, they have an isotopic signal of their tissues and guano characteristic of marine consumers, i.e., a relatively high $\delta^{15}N$ value (Hobson et al., 1994). Moreover, this value is related to the consumer trophic level and is lower in a Little auk *Alle alle* that feeds on copepods, than in a Glaucous gull *Larus hyperboreus* or Northern fulmar *Fulmarus glacialis* that is a top predator (Käkelä et al., 2007; Wold et al., 2011). Since seabird guano is the major source of nutrients for plants growing on the foot of cliffs, the plant tissues duplicate the isotopic signal of bird guano (Szpak et al., 2012; Zwolicki et al., 2016).

The aim of this study was to date the bird colonization in the Honsund area (SW Spitsbergen). We assumed that the origin of the fertile peatlands was synchronized with the development of bird colonies or at least that bird colony origin was recorded in peat profiles with significant changes in the isotopic composition of nitrogen and carbon. Then, we tried to correlate the timing of bird colony origin with environmental changes in the region of south Spitsbergen.

2. Material and methods

2.1. Study sites

We collected five peat sections in the area located on the northwestern shore of Hornsund fjord (77°N, 15–16°30′E) in the southwestern part of Spitsbergen (Fig. 1). The location and some characteristics of the studied peat profiles are given in Table 1. The bedrock in the area consists mainly of weakly to moderately metamorphosed sediments of Precambrian age. The climate and water characteristics are determined by the cold Sorkapp Current from the east and the warmer Atlantic waters of the West Spitsbergen Current. The present climate in the area is typical for the Atlantic Arctic region ($T_{mean} = -4.3$ °C; annual total precipitation is 434.4 mm) and is characterized by cold and dry winters ($T_{Jan} = -10.9$ °C; $P_{Jan} = 30.5$ mm) and cold, relatively wet summers ($T_{Jul} = +4.4$ °C; $P_{Jul} = 41.0$ mm, $P_{Sep} = 64.4$ mm) (Marsz and Styszyńska, 2013). The vegetation in study site is Ornithocoprophilous tundra (Skrzypek et al., 2015) with a *Sanionia uncinata-Straminergon stramineum* community (Hor 2, 7 and 8) and *Cerastium arcticum-Chrysosplenium tetrandum* community (Hor 1, 10) (Zmudczyńska et al., 2012). The study area is an important breeding site for seabirds. From the ten species that breed there, the most numerous is the Little auk *Alle alle*, followed by the Arctic tern *Sterna paradisaea* and Snow bunting *Plectrophenax nivalis* (Wojczulanis-Jakubas et al., 2008). In addition to breeding species, Barnacle geese *Branta leucopsis* exploit the tundra as their foraging and resting area.

2.2. Peat retrieving

The peat monoliths were cut off with a knife, described in the field and transported and stored in plastic bags at a temperature of 4 °C until subsampling. The sections of peat were subsampled every 0.5 cm with a scalpel. The known amount of sediment was weighted and dried in 60 °C over 48 h. Then, the sediment was divided for additional analyses.

2.3. Element analysis

The subsamples of 1–5 cm^3 of wet sediment were dried, ground in an agate mortar and homogenized. The concentrations of total organic carbon (TOC), total nitrogen (TN), total hydrogen (TH) and total sulphur (TS) were measured with the Vario Cube elemental analyser. Five to ten milligrams of sediment were transferred into pre-weighted tin capsules.

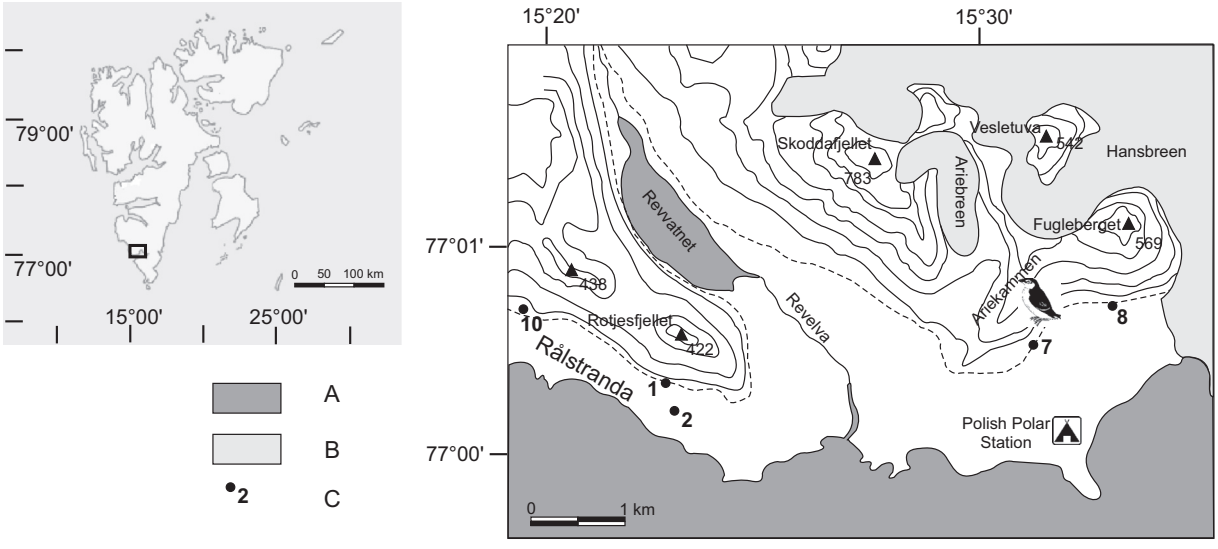

Fig. 1. Location of studied sediment sequences in the Hornsund area. A – waters, B – glaciers, C – location od study sites. The biggest bird colonies were marked with bird symbols.

Table 1
Study sites locality.

Site name	Longitude	Latitude	Elevation (m a.s.l.)	Landform	Peat sequence thickness (cm)
Hor 1	15°22′40.8″ E	77°00′21.8″ N	72	On the higher nival moraine	20
Hor 2	15°23′13.0″ E	77°00′16.0″ N	26	Raised marine terrace	25
Hor 7	15°32′10.0″ E	77°00′39.4″ N	40	In the base of nival moraine slope, close to the auk colony	6.5
Hor 8	15°34′00.8″ E	77°00′48.0″ N	47	In the base of nival moraine slope	11
Hor 10	15°19′19.6″ E	77°00′46.2″ N	58	On the middle nival moraine	25

Then, samples were burned at a temperature of 1150 °C, and the obtained gases (CO_2, N_2, H_2O and SO_2) were separated on a chromatographic column and measured with a thermal conductivity detector. Sulfuric acid was measured with every series of samples as a standard. Measurement uncertainties for C, H, N and S were 0.6, 0.21, 0.18 and 0.43%, respectively.

2.4. Age determination

Sediment sequences were dated using radiometric methods. For the younger sections of sediment sequences, a lead-210 method was applied (Appleby, 2001). The activity of ^{210}Pb was determined indirectly by alpha measurements of ^{210}Po activity. A known amount of ^{208}Po was added to the weighed sample as an internal yield tracer. Polonium was separated from the sample using strong hydrochloric and nitric acids, and then, it was deposited onto silver disks (Flynn, 1968). The activity of ^{210}Po and ^{208}Po was measured using a DUO alpha spectrometer produced by EG&G ORTEC. The ages of the samples were calculated based on a constant rate of supply (CRS) model (Appleby, 2001). Additionally, caesium ^{137}Cs was applied as a stratigraphic marker. The ^{137}Cs was measured with gamma spectrometry using Canberra Packard germanium detector Be5030 with low background geometry.

In the selected sediment cores (Hor 7 and Hor 8), radiocarbon dating of plant remains was done (Table 2). Radiocarbon activity was measured with an AMS spectrometer in the Poznań Radiocarbon Laboratory. The results were calibrated using OxCal ver. 4.2 software (Bronk Ramsey, 2009) and IntCal13 calibration curve (Reimer et al., 2013).

Age-depth models combining radiocarbon and lead dates were calculated using the MOD-AGE algorithm (Hercman and Pawlak, 2012; Hercman et al., 2014). The models based on the randomized distribution of ages (5000 randomizations per date) and age-depth functions were matched using the LOESS (locally weighted scatterplot smoothing) method. A Monte Carlo simulation was used for confidence band estimations of the age-depth curve. The age of the older horizons was calculated by extrapolation of the sedimentation rate from the oldest samples with direct measurements of unsupported ^{210}Pb activity.

2.5. Isotopic analysis

The organic nitrogen and carbon isotopic compositions were analysed in dry sediment samples using an elemental analyser Thermo Flash 1112HT connected with a Thermo Delta V Advantage mass spectrometer in continuous flow mode. The samples were first washed with ultra-pure water to remove pore water; then, they were dried at 60 °C over 48 h and treated with weak hydrochloric acid to removed detrital carbonates and dried again. Measurements were calibrated with USGS 40, USGS 4 and IAEA 600 standards. The results were reported as per mill (‰) deviations versus atmospheric N_2 (δ^{15}N) and Vienna Pee Bee Belemnite (δ^{13}C). The analytical errors (1 SD) for the δ^{13}C and δ^{15}N measurements were 0.17‰ and 0.24‰, respectively.

Principal component analysis (PCA) was applied to identify the main shifts in stable isotope records. Then, analysis of similarities (ANOSIM) was used to test significance difference between identified groups of samples (Clarke, 1993). The statistical computations were done with PAST 3.10 software (Hammer et al., 2001).

3. Results

3.1. Peat sequence chronologies

The age-depth modelling of the studied sediments were based on radiometric measurements of ^{210}Pb and ^{14}C activity. The lead data were available for all the sequences, while radiocarbon dating was conducted for the material from sequences Hor 7 and Hor 8 (Table 2).

The specific activity of unsupported ^{210}Pb in surface sediments varied over the sites and was the lowest in Hor 2 (80 Bq kg^{-1}) and the highest in Hor 8 (750 Bq kg^{-1}). The activity of ^{210}Pb decreased generally with depth in all the sediment sequences (Fig. 2). The worst fit of the activity profile to the model exponential function (relatively low R^2 value) was recorded in Hor 2. This, together with low activities in that sediment sequence, suggests post depositional migration of lead along sediment column. Hence, dating results and age-depth model calculation for that site should be treated with caution (Fig. 3).

3.2. Elemental and isotopic signal from peat sequences

3.2.1. Hor 1

Sequence Hor 1 started with a relatively high content of organic carbon (>30%) and nitrogen >2%) (Fig. 4). The isotopic signal for C and N indicated relatively high proportions of heavier isotopes. The δ^{15}N was over 16‰ at that time. Then, in sediments dated as the second half of 18th century, the C and N content decreased to <15% and 1%, respectively. The δ^{15}N also decreased and did not exceed 13‰. After this, C and N content increased and fluctuated to the top of the sequence. The maximal percentages were 40% for C and 2.6% for N and were noted at depths of 6 cm and at the surface. The δ^{15}N declined over entire

Table 2
Radiocarbon dates of macrofossil samples.

Sample name	Lab. no	Profile	Depth in profile (cm)	Dated material	^{14}C date (yr BP)	Calibrated ages (2σ)
Hor 7_5.5	Poz-53809	Hor 7	5.5	*Salix* wood	165 ± 30	1662 CE (17.1%) 1706 CE 1720 CE (49.4%) 1819 CE 1832 CE (10.3%) 1881 CE 1915 CE (18.5%) 1954 CE
Hor 7_6.5	Poz-53810	Hor 7	6.5	*Salix* wood	135 ± 30	1671 CE (40.7%) 1779 CE 1798 CE (39.7%) 1892 CE 1907 CE (15.1%) 1943 CE
Hor 8_11.0	Poz-53811	Hor 8	11.0	*Salix* wood	365 ± 30	1448 CE (51.6%) 1529 CE 1544 CE (43.8%) 1634 CE

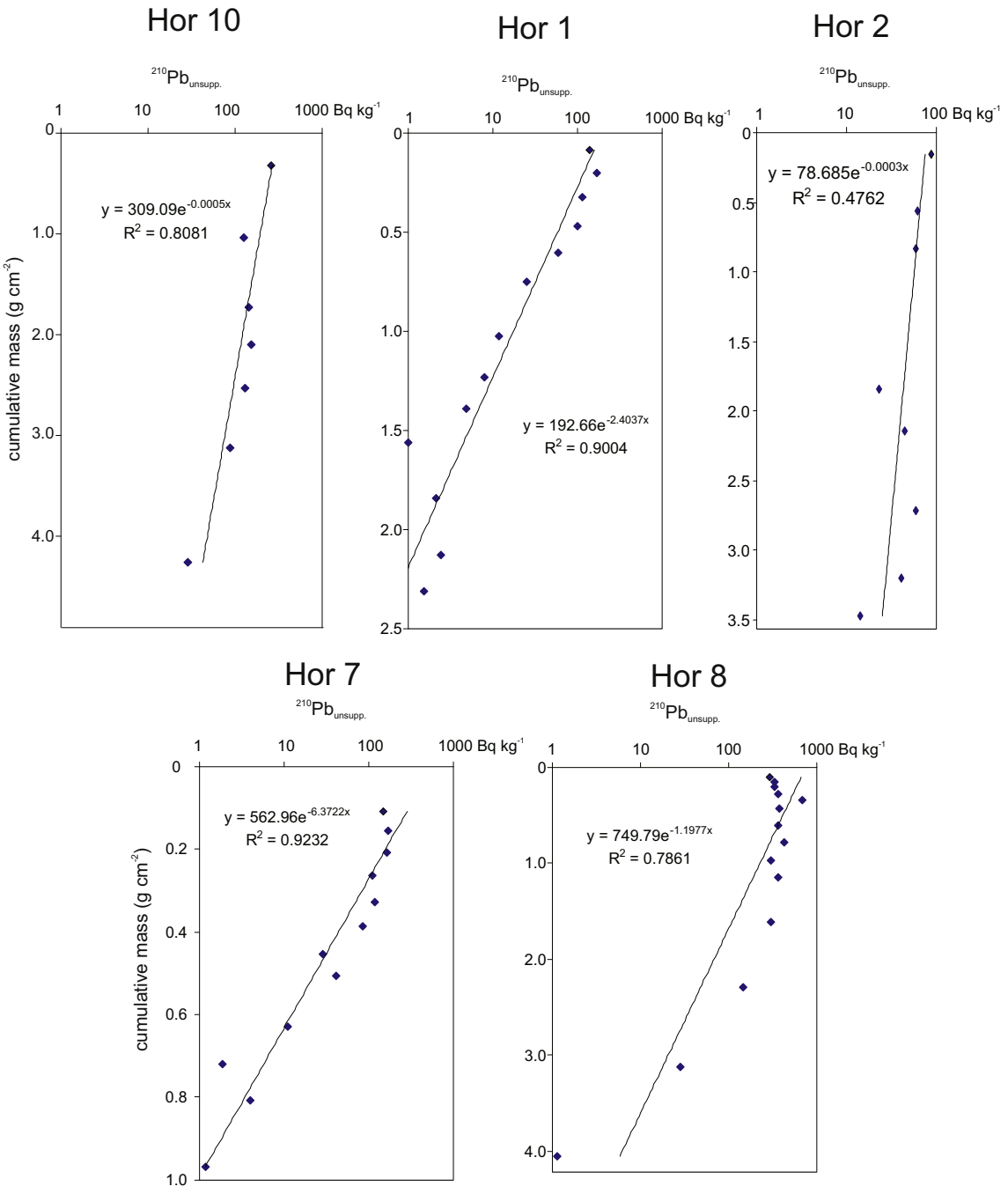

Fig. 2. Activity of unsupported ^{210}Pb (Bq kg^{-1}) in function of cumulative dry mass (g cm^{-2}) in studied peat sequences.

the 20th century to the 10–11‰ in the youngest samples. PCA and ANOSIM results indicate two significant changes in δ^{15}N records: first is decline at the end of the 19th century ($p = 0.002$, $R = 0.58$) and the second is further decline from 1990 ($p < 0.001$, $R = 0.77$).

3.2.2. Hor 2

The organic nitrogen concentration was stable and followed the organic carbon content in this sequence until the 1920s. After that time, both C and N decreased during the 20th century from 40 to 14% and from 2.7 to 1.1%, respectively. During the past two decades, N continued to be low and stable, while C increased again to 35–40%. Stable isotope records of C and N were not as parallel. The δ^{13}C was between −25 and −24‰ until the first several decades of the 19th century. Then, it decreased to −27‰ and fluctuated during the 20th century, with prominent shifts to the higher value of δ^{13}C in the 1930s and 1980s. The core can be split into 4 zones according to δ^{15}N value changes. The first zone is characterized with low values of δ^{15}N and it ended in the middle of the 18th century. Then, concentration of ^{15}N during the second zone increase significantly ($p < 0.001$, $R = 0.85$) from 4 to 10‰ until the mid-19th century. The third period of δ^{15}N record is characterized with generally stable values (~10‰) and it lasted to 1990, when ^{15}N concentration significantly ($p < 0.001$, $R = 0.68$) increased.

3.2.3. Hor 7

This sequence consists of two parts. The first part (9–7 cm) is glacial/fluvioglacial clay, which is characterized by a low content of organic matter. The C content in the peat part of the Hor 7 sequence (7–0 cm) varied between 35 and 40%, and nitrogen consisted of 1.5–2.5% in the

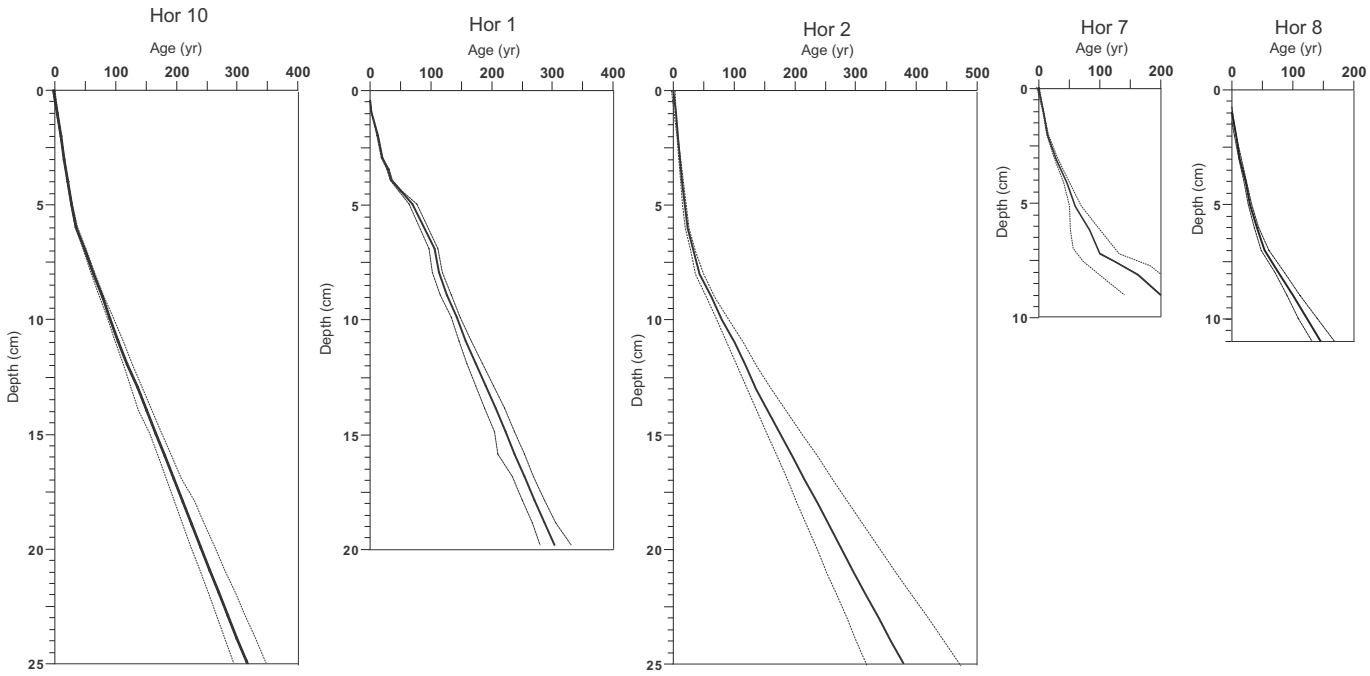

Fig. 3. Age-depth models (solid lines) for studied peat sequences. Functions' confidence bands marked with dashed lines.

dry mass. The carbon isotope decreased from −22.5‰ in the bottom part to −25‰ at the sediment surface. The $\delta^{15}N$ was relatively low in the part with low organic matter content, but in the part with peat, it increased significantly ($p < 0.001$, $R = 0.99$) to over 12‰.

3.2.4. Hor 8

The sediment sequence starts with fluvioglacial deposits with terrestrial plant debris (below depth 11.0 cm). The C content increased from 6 to 46% over the sequence. The N content increased from 0.5 to 1.8% until the 1980s, and after that time, it fluctuated between 1 and 2.3%. The $\delta^{13}C$ decreased from −25 to −29‰ between the 1870s and 1970s, and the $\delta^{15}N$ was almost stable (8–9‰) in this period with no significant changes.

3.2.5. Hor 10

The C and N content changed in the same way over the entire sediment sequence ($R^2 = 0.96$). and in the first part of the core (until 1930) were below 10 and 1%, respectively. The relatively strong

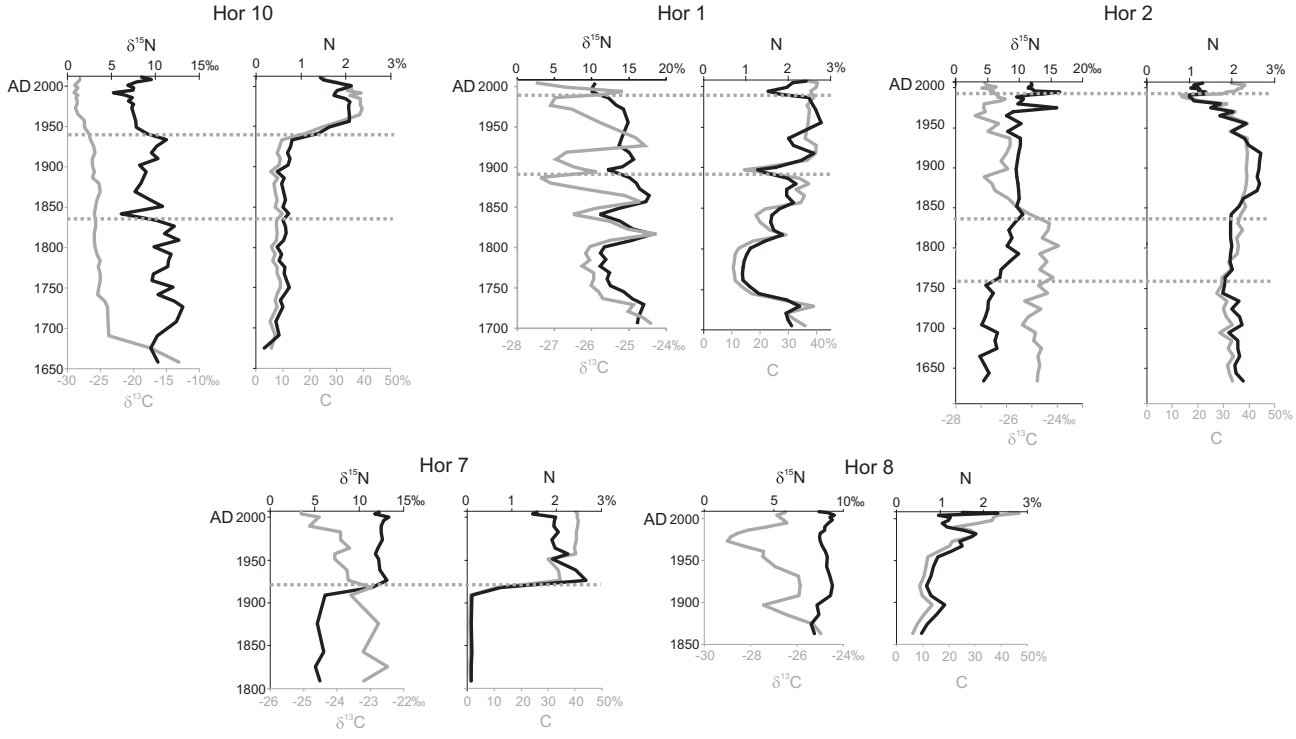

Fig. 4. Total organic carbon (grey) and nitrogen (black) concentration and isotopic signals in studied peat profiles. The statistically significant changes in $\delta^{15}N$ records were marked with grey dotted lines.

increases in both elements were recorded in the uppermost 8 cm after 1940. The carbon content increased to 38–39%, and the nitrogen content exceeded 2%. Then, the content of both elements decreased during the 1990s and 2000s. The $\delta^{13}C$ increased over the entire sequence from −24 to −29‰. The concentration of ^{15}N changed, and $\delta^{15}N$ fluctuated in range 9–11‰. Based on PCA results, 3 significant ($p < 0.001$, $R = 0.52$) stages in $\delta^{15}N$ record can be distinguished: (1) the generally higher values from the beginning of the record to the half of the 19th century, (2) transitional period from the 1840s to 1940s and (3) modern times with relatively low concentration of ^{15}N.

4. Discussion

4.1. Reliability of sediment dating

The chronology of sediment sequences is critical in paleoecological studies. Reliable age-depth models reported with their uncertainties allow the placement of specific changes in the paleoecological records over time and compare them between sites. However, the high organic content of peat deposits (often >95% organic matter on a dry-mass basis especially in ombrotrophic bogs) and the high cation-exchange capacity of *Sphagnum* moss species growing in poor fens and bogs have caused many challenges for dating peat sediments (Turetsky et al., 2004).

We applied radiometric dating based on the radioactive decay of the ^{210}Pb isotope – a member of U-series decay chain. The ^{210}Pb method was used successfully to build a chronology of lake sediments that were 100–150 years old (e.g., Gąsiorowski and Hercman, 2005; Gąsiorowski, 2008; Sienkiewicz et al., 2017). However, the method can be applied after some assumptions, including the assumptions that there is no possibility of post-depositional sediment mixing and no migration of radio lead along the sediment column. The second assumption is sometimes not completed in peat profiles (van der Plicht et al., 2013). The best method to validate the age-depth model based on ^{210}Pb measurements is the application of an independent method of dating. Caesium-137 activity is often used as an additional stratigraphic marker. ^{137}Cs is an artificial isotope released to the atmosphere during nuclear weapons tests and nuclear plant accidents. The most prominent peaks in caesium profiles recorded the most active period of nuclear tests in the 1960s and the Chernobyl nuclear plant accident in 1986. Unfortunately, radiocaesium in some condition, including peat deposits, can be remobilized and transported with pore water along the sediment column. Łokas et al. (2013) described this process for some peat profiles located close to the study area. We discovered a similar behaviour of caesium in sites Hor 7 and Hor 8. In the latter site, radiocaesium activity concentrated on the horizon of 10 cm, where its activity increased over 325 Bq kg^{-1}. A relatively high value of ^{137}Cs activity was also reported from other sites associated with seabird colonies in Spitsbergen (Gwynn et al., 2004) Because of that, we used radiocarbon dating instead of caesium stratigraphy to validate age-depth models for these sites.

In the studied peat profiles, the age of the beginning of peat sedimentation decreased from the west (closer to the fjord mouth) to the east. The age of the peat in the Hor 10 site is at least 300 years old, and a similar age was calculated for the relatively close sites Hor 1 and Hor 2. The peat in the sites located to the east, up to the fjord, is much younger. The detrital sediments on the floor of the sequence for Hor 8 were dated on 365 ± 30 BP (Table 2), while the beginning of peat sedimentation was only 100 years. The radiocarbon date from that site (Table 2) dated, indirectly, the minimum age of the Hansbreen glacier retreat from this locality.

4.2. Isotopic indicators of bird colonization

The isotopic signal of nitrogen in Arctic peat is generally characterized by relatively low $\delta^{15}N$ values. The peat sequence from the Vorkuta region was reported as ranging from −0.6 to +5.0‰ (Andersson et al., 2012). Some Arctic environments are even characterized by lower values, from −5.5 to −1.5‰, which are the result of the uptake nitrogen released during bacterial decay (Skrzypek et al., 2008, 2015). On the other hand, the peat from fertile environments under seabird cliffs is characterized by relatively high $\delta^{15}N$ values (e.g. Yuan et al., 2010; Janbu et al., 2011; Davidson et al., 2018). The enrichment in ^{15}N in peat is a result of washed bird faeces and other organic wastes from the bird colony area. The higher proportion of the heavier isotope of nitrogen is a derivative of the seabird diet enriched in ^{15}N. The most numerous bird species nesting and feeding in the Hornsund area is the little auk (Wojczulanis-Jakubas et al., 2008). The birds feed mainly on marine zooplankton and hence have a stable isotope signature characteristic of marine predators. The main prey of little auk are copepods of *Calanus* spp., which have an average $\delta^{15}N$ value in the water west of Horsund of 7–9‰ (Sato et al., 2002). The nitrogen isotope ratio in the body tissues of the little auk in Hornsund is 13.8 ± 0.3‰ (Fort et al., 2010), while in their faeces is 8.1 ± 0.5‰. Some other seabird species can have even higher values of $\delta^{15}N$ in their tissues, even over 15‰ (Forero et al., 2004). The peat developing under bird cliffs utilizes organic matter from the colony and receives its isotopic signal from that organic matter. This clear contrast between normal and fertile peat can be used to detect the moment of bird colonization at a specific site. We found the input of organic matter of marine origin in all the studied peat profiles. However, the ^{15}N distribution along the peat column varied in most of the profiles. The most prominent increase in $\delta^{15}N$ was noticed in the peat profile Hor 7, clearly indicating the beginning of bird impact on that site. On the other hand, in the peat profile located to the west, we noticed a gradual decrease in ^{15}N concentrations, suggesting a decline of bird activity at these sites. Interestingly, this finding did not cause a significant drop in productivity, expressed as concentration of TOC and TN (Fig. 4). At site Hor 10, the organic matter content clearly increased after 1950. We interpret this change as an effect of the increasing summer temperatures and the greater strength of the western storms rather than the effect of an extra input of nutrients from bird activity. The Hor 2 site is an exception and no decreasing trend in $\delta^{15}N$ was recorded there during the last century. However, the Hor 2 is located on a raised marine terrace, not in the border of former bird colony. This area is supplied by water (and nutrients) from a nival moraine above, where site Hor 1 is located. So, the site may be constantly influenced until present time by nitrogen weathered and transported from the colony area.

4.3. Climate as the major factor driving seabird colony origin and fertile peat development

Congregating individuals, including colonial breeding, is an effective anti-predation strategy demonstrated by different groups of animals. Over 90% of seabirds are colonial (Danchin and Wagner, 1997), proving the high efficiency of this life strategy in marine ecosystems. Colony existence, size and density are determined by several factors, including access to sufficient food resources and availability of space for nesting. In case of the little auk from the Hornsund area, the major food type is marine zooplankton, namely, copepods, and in a lesser quantity amphipods and larval fish (Wojczulanis et al., 2006). The birds explore both more productive Arctic waters and warmer but less productive Atlantic waters. The little auk can fly relatively long distances during one trip to their feeding area. In the Horsund area, the maximal distance during a single trip is 50–65 km from the colony, and the total length of the trip can be over 150 km (Jakubas et al., 2013). In other regions of Spitsbergen, the auks can fly even longer distances, up to 150 km from the colony and over 300 km during a single trip. The distance between the two studied bird colonies in Hornsund, the old one in Rotjesfjellet (West) and the new in the Ariekammen (East), is only 4 km (Fig. 1). This small distance, in the context of the possible length of a single trip, excludes the changes in position of foraging locations as a factor determining the expansion of birds deeper into the fjord.

The most likely reason for the migration of the birds into the fjord is the accessibility of new areas for nesting related to glacier retreat after the Little Ice Age. The optimal nesting location for little auk should have southern exposure, a presence of a high number of crevices sufficient for nesting and isolation from glacial water. Previous studies reported a significant shrinking of glacier area and volume in the Hornsund region since the beginning of the 20th century (Błaszczyk et al., 2013). This process was visible in the vicinity of the little auk colony in Ariekammen, especially in the case of the Ariebreen glacier located just to the northeast of the bird colony (Owczarek et al., 2014). The total ice volume of the glacier decreased by ~75% during the 20th century (Lapazaran et al., 2013). The decrease in the glacier's direct-influence zone, namely, the permafrost zone, might promote bird colonization on the site. A similar or even more direct effect on the colony on the southern slopes of Ariekammen had the Hans glacier. The terminal moraine of the Hans glacier dated on the Little Ice Age is located only several hundred metres from the present bird colony (Lindner et al., 1992). The Hans glacier could effectively restrict little auk colonization in this area. The regression and melting of the glacier probably before 1650, and this process allowed the development of peatland at site Hor 8 only after 1850 (Fig. 4).

Little auks preferably chose talus or rock debris on gentle mountain slopes as nesting habitats (Stempniewicz, 1995). The most important advantages of this strategy are the lack of competition for breeding sites and less dependence on climatic factors. In fact, little auks from Hornsund prefer slopes with southern and east-southern exposure, which offer higher insulation and isolation from western storms. The largest and most densely inhabited colonies are in talus cones and moraines of the south-southeastern slopes. The influences of morphology and microclimate can also be seen in nearby sites of site Hor 1 and Hor 2. The peat started to grow several decades earlier in Hor 2 than in Hor 1, which is located at the higher elevation (Table 1).

The sites located deeper in the fjord (Ariekammen) might attract birds in several ways. First, the area of Ariekammen is better isolated from direct strikes from strong storms from the Atlantic. Second, this area is less penetrable by predators. In fact, lower predation is also related to the fact that the Ariekammen area is protected from strong winds. The most important predator of the little auk in the Hornsund area is the gull *Larus hyperboreus* (Stempniewicz, 1995). Due to their body construction and type of flight, gulls have an advantage over little auks during strong winds. As a result, gull predation on auks is more effective in places open to western, strong winds and on open waters. The direct influence of human presence in the close vicinity of the colony should also be considered. The Polish Polar Station, located just 1 km south-east of the colony, was previously used as a base for trappers and hunters. Scientists and to a larger extent hunters have limited the number of arctic foxes, the major terrestrial predator of little auks, that penetrated the area of the colony.

5. Conclusions

We find, that all study sequences of peat are younger than ~400 years, what is relatively young comparing to other little auk peat sites in the region (Yuan et al., 2010; Davidson et al., 2018). In most of the sequences, the stable isotope records indicated high value of $\delta^{15}N$ in the entire sediment profile, suggesting the input of N_{org} is of marine origin. In the peat section Hor 7 located in the Ariekammen slope, we noted relatively low values of $\delta^{15}N$ at the bottom part of the sediment sequence and then a strong change to a higher concentration of ^{15}N. This increase, dated ~80–100 years ago, was recorded in sites located close to the biggest colony of little auks in the Horsund area. It suggests that these bird colonies are relatively young, and their origin is related to the environmental changes during the 20th century, probably climate warming. Simultaneously, the origin of the Ariekammen colony and the decrease in bird impact on peat located closer to the fjord mouth were recorded, indicating the migration of the main bird colonies into the fjord.

Future environmental changes, especially climate warming, can accelerate further changes in little auk behaviour and cause their migration into new nesting localities in the Hornsund region. Acceleration of glacier retreat uncovers new areas for bird nesting. Other factors can include pressure from new predators. Climate warming and the decrease in marine ice cover have caused polar bears *Ursus maritimus* to starve during the summer, making them more likely to explore bird colonies during the nesting season (Prop et al., 2015).

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